

Ascertaining life cycle inventory data for electrical discharge machining

Gamage, Janaka R.; DeSilva, Anjali K.M.; Harrison, Colin; Harrison, David

Published in:
Procedia CIRP

DOI:
[10.1016/j.procir.2015.12.091](https://doi.org/10.1016/j.procir.2015.12.091)

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link to publication in ResearchOnline](#)

Citation for published version (Harvard):

Gamage, JR, DeSilva, AKM, Harrison, C & Harrison, D 2016, 'Ascertaining life cycle inventory data for electrical discharge machining', *Procedia CIRP*, vol. 41, pp. 908-913. <https://doi.org/10.1016/j.procir.2015.12.091>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please view our takedown policy at <https://edshare.gcu.ac.uk/id/eprint/5179> for details of how to contact us.

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Ascertaining life cycle inventory data for electrical discharge machining

Janaka R. Gamage^{a,*}, Anjali K.M. DeSilva^a, Colin Harrison^a, David Harrison^a *^a*School of Engineering and Built Environment, Glasgow Caledonian University, Cowcadenns Road, Glasgow G4 0BA, United Kingdom** Corresponding author. Tel.: +44-141-331-1201; fax: + 44-141-331-3005. E-mail address: jr.gamage@gcu.ac.uk**Abstract**

Sustainable manufacturing systems require accounting for both product and process level environmental impacts. Established methods and databases are available for product level environmental impact assessment. However, there is a lack of data for process level or use phase assessments despite these being responsible for a significant share of the total environmental impact. This lack of data is even further exacerbated for unconventional machining (UCM) - unit process Life Cycle Inventory (LCI) data for UCM processes has particularly limited records in LCI databases. Electrical discharge machining (EDM), which is the most widely used UCM process, is reported as much less energy efficient compared to conventional machining processes. In addition to that, EDM produces wastes in solid, liquid, gas and aerosol form increasing its environmental footprint. The purpose of this study is to ascertain LCI data for EDM processes and thus to facilitate improved life cycle assessment during the use phase. The study takes insights of CO2PEI!-methodology, a systematic inventory analysis of the use phase of manufacturing unit processes. Case studies are carried out with an industrial die and mould manufacturer. The resultant data for die sinking and wire EDM is then compared with publicly available data. Challenges of generalising LCI data are discussed with future improvement potentials.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

Keywords: Sustainable machining; Electrical discharge machining (EDM); Life cycle inventory

1. Introduction

Being a world leader in several manufacturing sectors, the European mechanical engineering sector has 37% of the global market share. In 2012 the manufacturing sector has generated Euro 7,000 billion turnover employing over 30 million persons directly [1]. Advanced manufacturing technologies for clean production, i.e. technologies to increase manufacturing efficiency in the use of energy and materials, and drastically reduce emissions, have been identified as a key area of concern by the European commission. Though the manufacturing sector plays a vital role in the global economy it continues to cause intensified pressure on the environment [2].

Tools and methods have been developed to assess the life cycle of products using popular life cycle inventory (LCI) data bases. However there is a lack of LCI data available for manufacturing processes at unit process level [3]. This is more

crucial for unconventional machining practices [4] having lack of record of studies focused on sustainability of unconventional machining processes [5]. Machining processes beyond traditional machining, which avoids physical contact of tool and work, such as electrical discharge machining (EDM), electrochemical machining (ECM) and laser beam machining (LBM) are referred to as unconventional machining (UCM) in this paper.

This paper analyses and presents how to ascertain process level LCI data using two case studies of die sinking EDM and wire EDM. Apart from energy data inventorying, it includes a discussion on how to allocate direct and indirect resources for the LCI. Aluminum alloy (3003) is used as the work material with a copper electrode for diesinking and with a brass wire for wire EDM. Further, it extends the analysis to assess the environmental impact of EDM using generated LCI. The paper concludes with limitations and directions for further research.

2. State-of-the-art

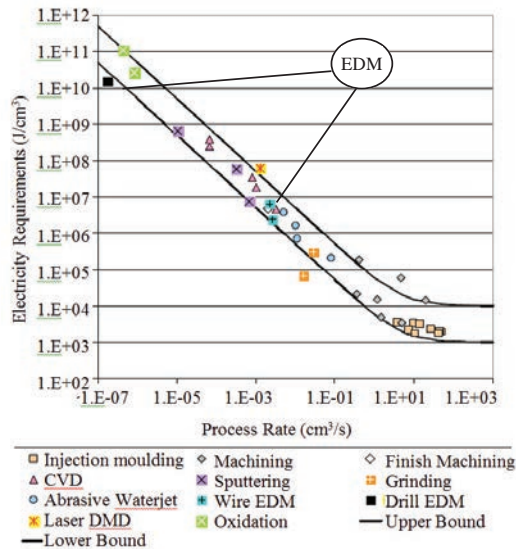


Fig. 1. Electrical energy consumption of manufacturing processes [6].

The EU and fourteen other members of World trade organisation (WTO) including USA and China have launched a new initiative in January 2014 to reward the practices that strive to achieve environmental/climate objectives by eliminating tariffs and barriers to trade in environmental products [1]. One of the main contributors to the environmental impact of any manufacturing process is electrical energy. An electrical energy consumption study of several manufacturing processes is illustrated in Fig. 1. It can be identified that wire EDM and drill EDM consumes energy in a range of 6^{th} to 10^{th} degree of joules per cubic centimetre (J/cm^3) of material removal which is higher than most other processes depicted. Further, it can be derived that EDM has a slower process rate (cm^3/s) compared to conventional machining though it consumes from a hundred to a million times more electrical energy.

Apart from electrical energy there are other contributors to the total environmental impact. A study by Kellens et al. [4] on environmental assessment of EDM shows that dielectric is also a significant contributor to the environmental impact. As can be seen from Fig. 2, 43.4% of environmental impact is caused by dielectric fluid (hydrocarbon oil) whereas the contribution from electrical energy is 37.4% during an hour of die sinking EDM process. The three electrical energy consumers, the discharge process (37.4%), exhaust system (3.1%) and process cooling (0.6%), totals to 41.1% of environmental impact which is still less than the impact from dielectric. The way in which the LCI for emissions are calculated is also unclear. The method of analysis is ReCiPe Endpoint (H) referring the Ecoinvent v2.0 database for a copper tool and hard metal workpiece. As the type of work piece is not mentioned, it is difficult to compare the results with another study. However, it appears to be the only record of LCI generation of EDM during unit process level impact study published thus far.

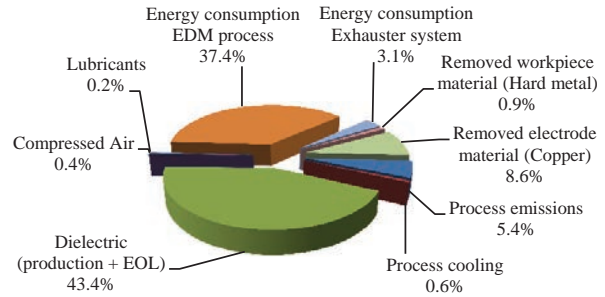


Fig. 2. Distribution of environmental impact during an hour of EDM roughing (Reproduced from [2], to meet publication standards).

3. Approach

The study aims to find out the process level LCI data of EDM. CO2PE! (Cooperative Effort on Process Emissions in Manufacturing) is a methodology proposed for systematic analysis of manufacturing unit process LCI data [3]. The framework mainly focuses on the actual use phase of the manufacturing process. It comprises with two levels of approach. The first is the screening approach where the assessment is made relying on publicly available data to calculate energy use, material loss and identifying variables for improvement. The second, in-depth approach contains four modules, a time study, a study of power consumption, a study on consumables and an emission study [7] which provides a more complete datasets for LCIs. The method is based on ISO 14040 (2006) and ISO 14044(2006) standards [8]. This study is using the in-depth approach to ascertain LCI data using EDM case studies.

3.1. Time study

It is evident that for unit process energy calculations of manufacturing processes are performed using time studies as they help identify the various use modes and their respective share in a given machining time span [9–11]. Therefore, it is important to have a track of time figures for which a particular sub unit, such as a pump, was in operation during a given session of machining. When it is difficult to monitor and record operating times with the unaided eye it is the common practice to use video recording methods to capture the activity [12]. Therefore two video cameras are used simultaneously to capture a machining process. One camera is fixed covering the full area of machine and the surrounding which will facilitate to identify operator interaction with the machine. The other is a hand held camera to capture local and much closer views of activities such as discharging and tank filling, which are not captured in the first camera. The way how the recordings were done with the second camera is captured in the fixed camera too. After recording, both video files are tallied to identify more accurate time values for each sub activity.

3.2. Energy study

The main source of energy during EDM is the electrical energy. The manufacturing unit process level electricity measurements can be performed by attaching meters directly to machines and/or sub units such as pumps and coolers. Use of electricity meters with time studies, is a practice used to calculate environmental impact of manufacturing processes and developing LCIs. Mobile instruments with metering and logging capabilities are preferred in the industry level research [13]. Energy data are collected using 'Elcomponents SPCmini®' current data logger, 'Fluke®' current clamp and nameplate data of sub units. In the cases of restricted access to attach metering devices, alternative arrangements were made.

According to ISO 14044:2006 LCA requirements and guidelines, the first step is to set the goal and scope definition. The study is focused and bounded only on the processing phase of EDM. The functional unit is set as machining of a given metal (Aluminium alloy) using electrodischarge machining with a given material removal rate. It includes both productive and non-productive activities.

4. Case studies

The case study protocol was developed with a pilot study in laboratory scale and with an observation visit to a leading die and mould machining service provider in Glasgow, UK. Main energy consuming sub units, resources needed and emission sources are identified. The data collection framework is then applied to state-of-the art die and mould facilitation centre which provides machining services and R&D services to the South East Asian region. Onsite data collection is done for a week to observe different work and tool materials. Time and energy studies are performed as explained. Resource consumption data are recorded by interviewing the workshop personnel and using manufacturer records.

4.1. Die sinking EDM case

The die sinking process is studied with a copper tool with intricate shape and relatively large contact area of 34.5 cm². The work is a 6 mm thick sheet of aluminium alloy (3003). The machine tool is a KingSpark® EDM NK series die sinker machine. The basic processes of EDM die sinking and how the three main impact streams associated with each process is illustrated in Fig. 3.

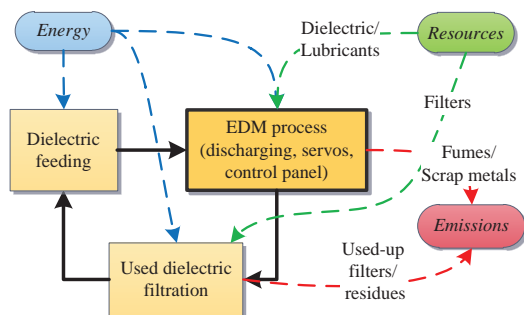


Fig. 3. Diesinking EDM process with impact sources.

4.2. Wire cut EDM case

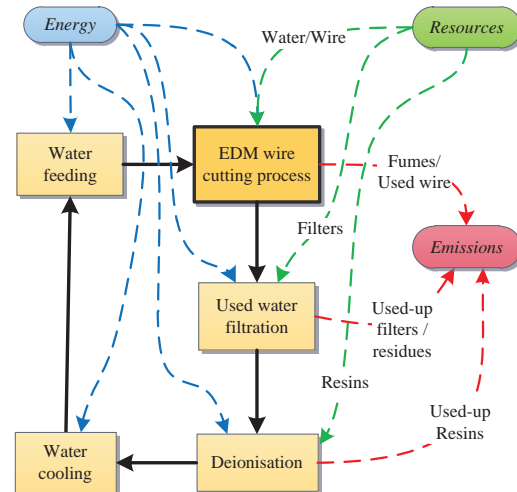


Fig. 4. Wire-cut EDM process diagram with impact sources.

EDM wire cut (WEDM) process is studied for 0.2 mm diameter brass wire with 6 mm thick sheet of aluminium (3003) work piece. The model of the wire cut machine studied is KingSpark® wire cut CNC AL-5 series machine. Fig. 4 shows the basic processes of WEDM with impact streams of energy, resources and emissions.

The machine setting up process is similar to that of any CNC machine. The programme is selected considering mainly the work material thickness, material type and required surface finish. The other parameters, such as cutting feed rate, wire advance, and gap voltage are automatically set once the programme is selected. However, these are manually changed as appropriate by operators or set to a pre-saved customised setting to achieve the required output. Once the programme is set, then the work is clamped and the cutting references are set to link the machine coordinate system. The tank filling command and the discharging command are made manually to initiate the machining process. Minimum supervision is needed as the process is automated to a great extent. A water cooler unit is in place to chill used water before re-feeding in to the tank unlike in die sinker.

5. Analysis and synthesis of LCI data

This section analyses and synthesises data collected during the case studies. The discussion follows the order of time, energy, resources and emission studies for each case.

5.1. Die sinker study

Three key process steps identified during the die-sinking process. The first, setting up step, includes machine zeroing, tool fixing, work clamping, work levelling and tank filling time. Setup time makes up to 28% of the total job time (Fig. 5). The next is the discharging process (64%) for which the time taken is highly dependent on the job.

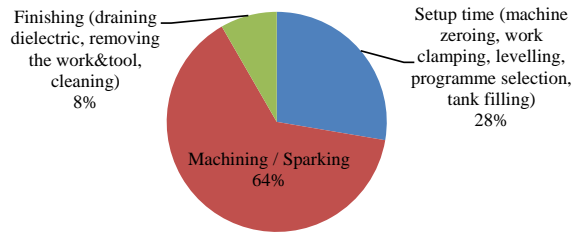


Fig. 5. Time study of die sinking EDM.

In this case, a relatively large copper tool (34.5 cm²) with an intricate shape took nearly two hours to machine a depth of cut of 0.758 mm with a material removal rate of 23.35 mm³/min. In light of generalising and comparison, the machining time is adjusted for one hour in Fig. 5. During machining there were some pauses for inspection and to clean any carbon deposits on the surface being machined which were excluded from machining time. The dielectric is drained and the work and tool are removed and cleaned during the finishing step which consumed the remaining 8% of time.

The total supply energy is recorded in the logger and sub units are studied using nameplate data and manufacturers' manuals. The video evidences and onsite observation data are used to identify and allocate energy consumers for each stage of machining. The data is then tabulated and analysed to generate the electrical energy consumption figures for each process step as shown in Fig. 6. Major portion of energy is consumed during sparking stage which sums to 85% of total. The discharge generator, feed pump and servos are the key contributors during sparking stage. Out of the other three process steps, setting up process shares 9% of the balance. When individual sub units are concerned, those can be ranked according to the individual energy consumption values as, discharge generator (32%), drives (25%), feed pump (27%), and controller unit (12%).

The consumables data are collected by interviewing the machine operators and onsite observations. A summary of resources data is listed in Table 1. Dielectric oil used in the machine is Esso-Lector 35 hydrocarbon oil. The dielectric level depends on the work and clamping apparatus dimensions. An automatic lubricator is in place and set to work 20 seconds every hour with a lubricant flow rate of 0.13 l/min. The two cartridge filters are replaced twice a year approximately.

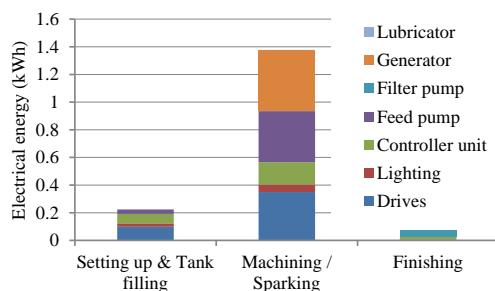


Fig. 6. Contribution from sub units to process energy during each stage of diesinking EDM.

Table 1. Resource data for die sinking EDM.

Resources/ consumables	Amount
Dielectric oil (Hydrocarbon - Esso Lector 35)	0.545 m ³ /hr
Lubrication oil (Mobil Vectra 2)	43 ml/hr
Cotton waste for cleaning	6.25g - (approx.)
Dielectric filters	2 units - replaced
(ø 15cm×45cm long-cartridge type)	twice a year approx.

For LCI purpose, reusing resources, such as dielectric, are apportioned using the life hours before maintenance replacement. For example, if the replacement period of dielectric is every 5 years, then it can be apportioned using annual machining hours. As EDM is a process, not a product, most of the solid and liquid resources listed in Table 1 can again be viewed as solid or liquid emissions as those are not consumed during machining process. In addition to those, removed work and tool material have to be considered in LCI. It is calculated that 1,401 mm³ of aluminium material and 6.3 mm³ of copper tool material are removed during one hour of machining. Gaseous emissions are not measured during case studies considering the practical limitations. However, for EDM setups without exhaust systems, the concentration for aerosols at the operator breathing zone has been found to exceed the permissible exposure limits for respirable particles of 5 mg/m³ [14].

Using generated LCI data can be then used to analyse LCA for EDM process of a given time as can be seen from Fig. 7. One hour is used as the time frame here to get sensible volumes of energy, resources and emissions figures. SimaPro® 8 software with Ecoinvent v3.0 LCI database is used for the analysis. : ReCiPe Endpoint (H) V1.11 / Europe ReCiPe H/A Single score method is used for the analysis. It is noted that the highest impact source is electrical energy with 57% and dielectric (27%) is causing almost half as the impact by electricity. This is a noteworthy deviation from previously published studies (Fig. 2) which may be due to the rationale behind LCI generation.

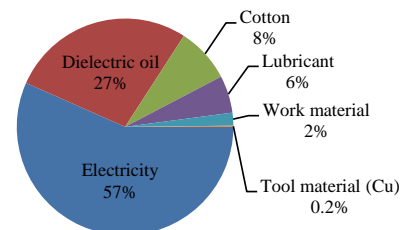


Fig. 7. Environmental impact of one hour of EDM diesinking.

5.2. Wire cut EDM study

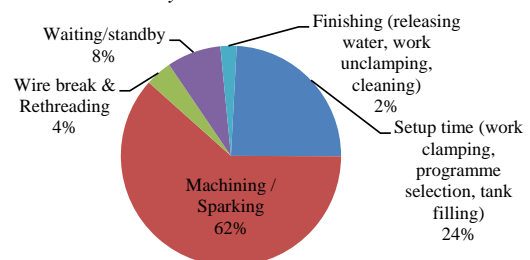


Fig. 8. Time study of wire EDM.

The setting up activities are similar to diesinking case apart from the wire loading. The time study data in Fig. 8 are shown for one hour of machining operation of cutting an aluminium gear wheel of pitch circle diameter 44 mm. Setting up activities have consumed 24% which is similar for die sinking case. The diagram represents one hour of sparking time and it should be noted that the machining time is highly dependent on the design of cut and the material type.

The value adding step, which is the machining step, consumed 62% of the total time and this excludes 4% of the wire rethreading times due to wire breakages. Frequent wire breakages causes revising the programme parameters such as wire feed and work advance to facilitate smooth operation. This period also consumes energy and causes resource ageing for LCI purposes. The balance 10% of the time is shared among standby and finishing steps during which, some of the sub units are consuming energy.

The power consumption pattern of the wire cut machine during the latter half of the machining process of Aluminium is plotted against time as presented in Fig. 9. The variations of the graph are mapped with the time study video data to explain the fluctuations. During machining/ discharging the power flutters around 6 kW. This comprises the power consumption by the discharger, ion exchange/auxiliary water pump, controller unit, servos and water cooler. The four major spikes reaching up to 7.5 kW are due to wire breakages. The second spike is labelled with letters 'A-D' for ease of explanation. The region 'A' denotes the power consumption during normal machining. The drop from 'A' to 'B' of 0.24 kW is the instance of wire breakage and can be explained by interruption of the discharge and servos. The peak 'C' is mainly caused by automatic triggering of the filter pump to filter out drained water. Spike 'D' of 0.85 kW explains the operation of rapid water fill pump to fill the tank again after rethreading. At point 'E' machining is completed with a drop in power of 0.28 kW. But the EDM machine keeps consuming energy at a rate of 5.8 kW (region F) to run the shutting down operations. The main contributors in region 'F' could be water cooler, controller unit, ion exchanger. The last segment marked by 'G' in the graph with a power level of 3.6 kW is the standby power consumption waiting for the next job. A detailed sub unit level energy consumption, using time study and power consumption data, is presented in Fig. 10.

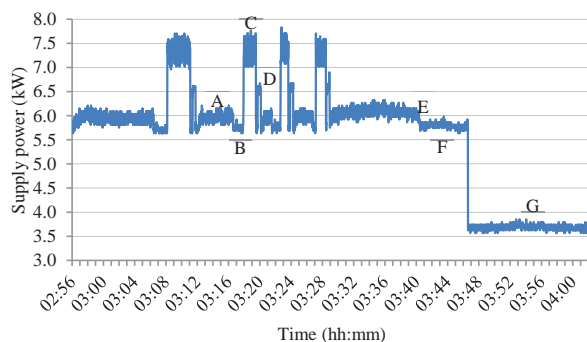


Fig. 9. Supply power variation during WEDM.

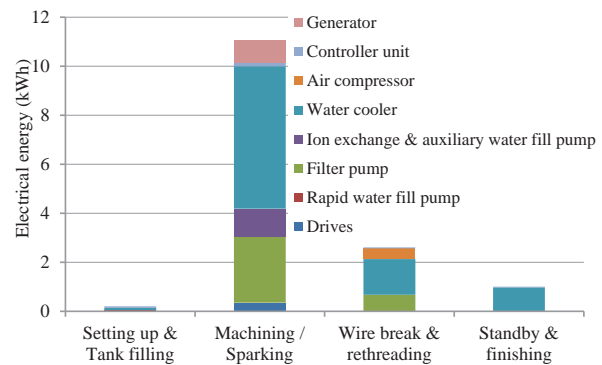


Fig. 10. Contribution from sub units to process energy during each stage of wire EDM.

This shows how each sub unit contributes to the total energy consumption during each stage of machining. Again it is the machining stage which consumes the highest consumption value of 74% of the total. The largest consumer during machining step is the water cooler followed by filter pump and then the ion exchange pump. During the whole machining process the water cooler (53%) and the filter pump (24%) together consumes 77% of total energy. The remaining 23% of energy is shared among ion exchange/auxiliary water fill pump (10%), generator (8%) and other units. The diagram represents energy consumption values for one hour of machining.

The consumables data for the given machining parameters of wire cut EDM are listed in Table 2. Used brass wire weighs 111 grams. The tank is maintaining a volume of 0.3 m³ of deionised water. A constant water flow rate of 2.8 m³/hr is also maintained to keep flushing the machining surface. However, for LCI calculations, maintenance replacement time of one year is taken as the use life of water and apportioned accordingly for the machining duration. 10 kg of deionising resins are required at a time for twice a year replacement approximately depending on machining loads. The clogged water filters trigger an alarm to warn operators of filter replacement. It is approximately once a year as per operator experience.

Used up brass wire and lost work material of 454.8 mm³ is considered as direct solid emissions. Similar to oil in the diesinking case, deionised water is reused in WEDM system. Therefore, deionised water is accounted based on replacement period. The water is replaced approximately each year to prevent sludge formation. Summarised LCI values are then used to generate the LCA for one hour of WEDM as shown in Fig. 11.

Table 2. Resource data for wire cut EDM.

Resources / consumables	Amount
Used up Brass wire ϕ 0.2 mm	111.12 g
Deionised water	1510 ml/h
Lubrication oil (Mobil Vectra 2)	43 ml/hr
Deionising resins	10 kg each time replaced twice a year
Water filter flush type (replaced when the pressure level exceeds 1.5kg/cm ²)	Once a year (approx.)

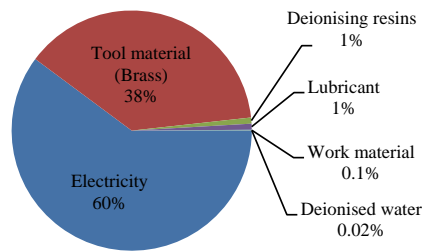


Fig. 11. Environmental impact of one hour of wire EDM.

It is interesting to note that, unlike hydrocarbon oil in die sinking case, the second largest impact of 38% is caused by the wire material brass. Electrical energy is responsible for 60% of impact and the balance is shared as shown. Deionised water has a negligible impact making it more environmental friendly compared to other dielectrics.

6. Conclusion

Case studies of die sinking and wire cut EDM are used to inventories the unit process energy consumptions, resource consumptions and emissions. Items, which would not be inventoried under typical product LCA, are accounted here in the process LCA. Most reusable resources are apportioned to unit time of machining based on their service time or replacement time. That was slightly different to the CO2PE!-method, where exact consumption figures are suggested through its in-depth approach. Method of tracing energy consumption figures can be applied to any unit process in a similar manner. During resource allocation it is required to understand the direct and indirect forms of resources. Direct resources, such as, for example, wire material in WEDM, are consumed during the process and are easy to trace and accounted for. Indirect forms of resources, such as dielectric liquid, have to be apportioned based on their use life which is a sensible option in view of complete resource accountability. Setting up and shutting down activities are performed irrespective of the machining duration. Therefore, energy and resource consumption during those stages are considered as fixed values and the machining duration as a variable.

Practical difficulty of measuring gaseous emissions and accounting for multiple material products, like dielectric filters, are the main limitation of this study. Further, the sub unit level energy figures could be improved by having individual metering devices attached to each unit which would be a much expensive task. Further research is underway to test different metals with different modes of cuts. Minimising energy and resource consumption during non-productive modes of machining would be a direction for further research. This could be focused at machine tool design level with advanced CNC algorithms.

Acknowledgements

The authors would like to acknowledge the participating industry partners, especially the die and mould facilitation and development centre, Moratuwa, Sri Lanka for facilitating data

collection. Further, they are grateful to the Glasgow Caledonian University for the PhD research grant and funding the expenses towards research publication.

References

- [1] European Commission. "Advancing Manufacturing - Advancing Europe" - Report of the Task Force on Advanced Manufacturing for Clean Production. Brussels: European Commission; 2014.
- [2] Duflou JR, Sutherland JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, et al. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Ann - Manuf Technol* 2012;61:587–609. doi:10.1016/j.cirp.2012.05.002.
- [3] Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR. Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. *Int J Life Cycle Assess* 2011;17:69–78. doi:10.1007/s11367-011-0340-4.
- [4] Kellens K, Renaldi, Dewulf W, Duflou JR. Preliminary Environmental Assessment of Electrical Discharge Machining. In: Hesselbach J, Herrmann C, editors. *Glocalized Solut. Sustain. Manuf.*, Springer Berlin Heidelberg; 2011, p. 377–82.
- [5] Gamage JR, DeSilva AKM. Assessment of Research Needs for Sustainability of Unconventional Machining Processes. *Procedia CIRP* 2015;26:385–90. doi:10.1016/j.procir.2014.07.096.
- [6] Gutowski T, Dahmus J, Thiriez A. Electrical energy requirements for manufacturing processes. *13th CIRP Int. Conf. Life Cycle Eng. Leuven Belg.*, vol. 5, 2006, p. 560–4.
- [7] Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR. Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies. *Int J Life Cycle Assess* 2012;17:242–51. doi:10.1007/s11367-011-0352-0.
- [8] ISO 14044. Environmental management - Life cycle assessment - Requirements and guidelines. British Standards Institute; 2006.
- [9] Devoldere T, Dewulf W, Deprez W, Duflou JR. Energy Related Life Cycle Impact and Cost Reduction Opportunities in Machine Design: The Laser Cutting Case. *LCE 2008 15th CIRP Int Conf Life Cycle Eng Conf Proc* 2008:412.
- [10] Devoldere T, Dewulf W, Deprez W, Willems B, Duflou JR. Improvement Potential for Energy Consumption in Discrete Part Production Machines. In: Takata S, Umeda Y, editors. *Adv. Life Cycle Eng. Sustain. Manuf. Businesses*, Springer London; 2007, p. 311–6.
- [11] Duflou JR, Kellens K, Dewulf W. Unit process impact assessment for discrete part manufacturing: A state of the art. *CIRP J Manuf Sci Technol* 2011;4:129–35. doi:10.1016/j.cirpj.2011.01.008.
- [12] Maynard's industrial engineering handbook. 5th ed. New York: McGraw-Hill; 2001.
- [13] Kara S, Bogdanski G, Li W. Electricity Metering and Monitoring in Manufacturing Systems. In: Hesselbach J, Herrmann C, editors. *Glocalized Solut. Sustain. Manuf.*, Springer Berlin Heidelberg; 2011, p. 1–10.
- [14] Evertz S, Dott W, Eisentraeger A. Electrical discharge machining: Occupational hygienic characterization using emission-based monitoring. *Int J Hyg Environ Health* 2006;209:423–34. doi:10.1016/j.ijheh.2006.04.005.